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Promoting Better Logging Practices in Tropical Forests

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Performance-based renewal conditions for tropical forest concessions provide a powerful incentive for loggers to adopt reduced-impact logging practices and to comply with minimum-diameter cutting limits — even with short concession agreements.

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Summary findings

In government-owned tropical forests, timber is often harvested under concession agreements with private logging companies.

Forestry departments typically impose logging regulations to minimize the negative environmental impacts of logging, but logging practices throughout the tropics appear to be undermining the sustainability of timber and nontimber benefits from tropical forests.

Boscolo and Vincent use bioeconomic simulations to test the empirical significance of several common recommendations for promoting better logging practices in tropical forests. They find that:

- Because of the effects of discounting, longer concessions give loggers little incentive to adopt reduced-impact logging or to comply with minimum-diameter cutting limits.
- Royalties can be used to encourage compliance with minimum-diameter cutting limits but discourage the adoption of reduced-impact logging. And per tree royalties, which encourage compliance with minimum-diameter cutting limits, tend to be less effective as revenue instruments.
- Relatively small performance bonds can be used to induce loggers to adopt reduced-impact logging, but very large bonds are needed to induce compliance with minimum-diameter cutting limits.
- Reduced-impact logging and minimum-diameter cutting limits both have significant positive effects on environmental indicators, but these benefits come at the cost of a substantial reduction in the timber value of the stand.
- Performance-based renewal conditions provide a powerful incentive for loggers to adopt reduced-impact logging and to comply with minimum-diameter cutting limits — even with short concession agreements.
- Performance-based renewal conditions sharply reduce the size of the performance bond needed to induce compliance with minimum-diameter cutting limits. Royalties, but not area charges, have a similar, although weaker, effect.

The authors' results also suggest that a cause of premature reentry into logged forests is minimum-diameter cutting limits that exceed minimum commercial log diameters, combined with weak control over access to logged-over forests.

This paper — a product of the Development Research Group — is part of a larger effort in the group to elucidate the economics of conservation policies. Copies of the paper are available free from the World Bank, 1818 H Street NW, Washington, DC 20433. Please contact Tourya Tourougui, room MC2-522, telephone 202-458-7431, fax 202-522-3230, Internet address ttourougui@worldbank.org. Marco Boscolo may be contacted at mboscolo@hiid.edu. September 1998. (52 pages)

PROMOTING BETTER LOGGING PRACTICES IN TROPICAL FORESTS: A SIMULATION ANALYSIS OF ALTERNATIVE REGULATIONS

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PROMOTING BETTER LOGGING PRACTICES IN TROPICAL FORESTS: A SIMULATION ANALYSIS OF ALTERNATIVE REGULATIONS

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I. INTRODUCTION

Most tropical forests are government-owned, with timber being harvested under concession agreements awarded to private logging companies. Those agreements tend to be short-term harvesting licenses lasting no more than one to a few years. In the absence of regulation, loggers can be expected to ignore the negative environmental impacts of logging, as they derive little or no financial gain from mitigating them. Forestry departments typically impose various logging regulations in an effort to minimize such impacts. Common ones include minimum diameter cutting limits, which prohibit the felling of trees below a specified diameter, and cutting cycles, which prohibit premature reentry of logged-over areas. Despite such efforts, much evidence indicates that logging practices throughout the tropics are undermining the ability of tropical forests to sustain flows of timber and nontimber benefits (Poore et al. 1989, Panayotou and Ashton 1992, Johnson and Cabarle 1993, Sist et al. 1997).

The study presented in this paper tests the empirical significance of several common recommendations for promoting better logging practices in tropical forests: in particular, making concession agreements longer, linking renewal of those agreements to logging practices, and using performance bonds to encourage compliance with logging regulations. It assesses how these recommendations affect both the economics of timber harvesting and the provision of environmental benefits. Regarding the latter, it focuses on carbon sequestration and biodiversity. It also examines the effects of timber fees and discount rates on economic and environmental outcomes.

The study focuses on two aspects of logger behavior: choice of logging technology and compliance with prescribed minimum diameter cutting limits. Logging technology can be viewed as ranging from highly damaging conventional logging at one extreme to "reduced impact logging" (RIL) at the other. RIL involves several distinct practices, including forest mapping, planning the logging operation, careful construction of logging roads and skid trails, climber cutting, directional felling, and minimal use of bulldozers (cf. Shahwahid et al. 1997). The study analyzes loggers' decisions about technology and cutting limits in two scenarios: (i) the *repeated harvesting* of a given forest stand (virgin forest for the initial harvest, second-growth forest for subsequent harvests), which occurs at a time delay of several decades (the cutting cycle); and (ii) the *sequential harvesting* of an annual series of different forest stands with identical characteristics (all virgin). The former gets at issues of sustainable forest management, while the latter gets at the mining of virgin timber stocks. In this way, the study examines both the long-run and short-run dynamics of logger behavior.

Long-term field data from actual logging operations spanning multiple cutting cycles would be ideal for studying these issues. Unfortunately, such data do not exist in any tropical country. Although new field experiments can, and should, be set up (and indeed they are, by such organizations as the Center for International Forestry Research and the Tropical Forest Foundation), these experiments will not yield results for years to come. As an alternative, this study uses a simulation approach to analyze logger behavior. Simulation is less directly grounded in data on actual behavior, but it complements field experiments by providing answers to key policy questions more quickly and by identifying areas of needed further research.

The paper is organized as follows. We begin by describing the models of forest growth and logger behavior that comprise the simulation model. The description of the forest growth model includes the indicators used to predict the environmental impacts of logging, and the description of the model of logger behavior includes the regulatory instruments analyzed. Next, we present and discuss the simulation results, dealing with repeated harvesting and sequential harvesting in turn. In the final section we highlight the principal conclusions that can be drawn from these results.

II. OVERVIEW OF THE SIMULATION MODEL

The forest growth model predicts recovery of the forest following logging. It predicts both the growth of residual (unharvested) trees and the recruitment (regeneration) of new trees. It is based on an unusually large data set from a 50-hectare research plot in a virgin rainforest in Pasoh Forest Reserve in Negeri Sembilan, Peninsular Malaysia. The plot, which the Forest Research Institute Malaysia established in 1985 (Manokaran et al. 1990), is, along with a sister plot on Barro Colorado Island in Panama, the most intensively inventoried forest plot in the tropics. It has been inventoried three times at five-year intervals, with data currently available from the first two inventories. Each inventory generates information on the species, dbh (diameter at breast height: 1.5 m above the forest floor), and spatial location of all free-standing, woody stems with a dbh $\geq$ 1 cm. The total number of stems in the plot is over 300,000, representing more than 800 tree species. The large number of individual trees, measured at two points in time, permits the statistical estimation of equations predicting the annual diameter growth of individual species or groups of species. Although these equations are based on data from a virgin forest, studies from similar forests elsewhere in Malaysia indicate that diameter growth rates differ little between virgin and logged-over forests over the long term (Wan Razali 1988, Primack et al. 1987). There is thus reason to believe that the simulation model provides reasonably accurate estimates of the forest's response to logging, despite being based on data from an unlogged forest.

The model of logger behavior treats the logger as being solely interested in maximizing the discounted sum of profits from logging. The logger's time horizon depends on the concession context (repeated or sequential harvesting), the length of the concession agreement, the logger's expectations about renewal of the agreement, and the logger's discount rate. The model predicts the number and size of trees harvested and the logging technology employed. Logging technology affects the amount of logging damage: the number of trees destroyed (killed) by logging. A study by Griffin and Caprata (1977), which continues to be regarded as the most reliable study on logging damage in Malaysia, was our source of information on logging damage rates.

In sum, the model of logger behavior gives the objective to be maximized—the discounted sum of logging profits—and the forest growth model gives the ecological constraints the logger faces. Solving the overall simulation model involves determining the combination of harvest level (to be precise, the number of trees in each species group) and logging technology that maximizes the former without violating the latter, under a given set of logging regulations.

III. THE FOREST GROWTH MODEL

Recruitment, growth, and mortality

Both the profitability of logging and the effectiveness of regulations in protecting environmental attributes of the forest depend on how the forest responds to utilization (see Figure 1). For this study we adapted the forest growth model developed by Boscolo et al. (1997) and modified by Boscolo and Buongiorno (1997). This model predicts the recruitment, growth, and mortality of individual trees in a representative hectare of the Pasoh plot, broken down by species group and diameter class. The model can be summarized as

$$\mathbf{y}_{t+1} = \mathbf{G}\,[\mathbf{y}_t - \mathbf{h}_t - (1 - 2/3_{\omega})\mathbf{D}\mathbf{h}_t] + \mathbf{c}\,, \qquad [1]$$

where $\mathbf{y}_t = [y_{ijt}]$ is a $1 \times mn$ vector indicating the number of trees of species group i (= 1, …, m) and diameter class j (= 1, …, n) alive at time t; $\mathbf{h}_t = [h_{ijt}]$ is a vector of the same dimension indicating the number of trees of species group i and diameter class j harvested at time t; $\mathbf{G}$ is a $mn \times mn$ matrix of growth (and, implicitly, mortality) and $\mathbf{c}$ is a $1 \times mn$ vector of recruitment parameters; $\mathbf{D}$ is a $mn \times mn$ matrix of logging damage parameters; and ω is a parameter related to logging technology (0 = conventional logging, 1 = RIL). This expression indicates that the state of the forest at a given time depends on the state of the forest before harvest, the extent of timber removals (harvest plus damage), the number of years since the last harvest, and the growth and recruitment parameters in **G** and **c**.

To enhance the tractability of the model, Boscolo et al. (1997) aggregated the hundreds of species in the Pasoh plot into three groups: dipterocarps (species in the family *Dipterocarpaceae*, which dominates the rainforests of Southeast Asia; denoted henceforth as D), other commercial species (O), and noncommercial species (N). They further aggregated individual trees in these groups into seven 10-cm diameter classes. Table 1 shows the structure of an average hectare in the initial virgin stand by species group and diameter class according to three standard forestry measures: number of trees, basal area (the sum of the cross-sectional areas of tree trunks at breast height), and timber volume net of defect. Note that dipterocarps account for most of the large-diameter trees and, consequently, most of the timber volume. Boscolo et al. (1997) provide a detailed description of the estimation of the recruitment, growth, and mortality parameters for these species groups and diameter classes. Appendix I provides a summary description.

Logging damage

Through the damage matrix **D**, the model reflects the fact that harvesting operations damage the residual stand, especially small trees that are killed by the felling and skidding of crop trees (Boscolo and Buongiorno 1997).[2] The elements of this matrix, d_{ij}, are the number of small trees (dbh = 10-20 cm) of species i killed by harvesting a tree of size j. The parameters d_{ij} were calibrated by assuming that the felling of all commercial trees above 60 cm would kill half the trees in the 10-20 cm dbh class. This assumption was based on information in Griffin and Caprata (1977), which indicated that the 10-20 cm class suffers the highest rate of damage among dbh classes $\geq$ 10 cm. Based on a study of RIL in east Malaysia by Pinard et al. (1995), we assumed that full implementation of RIL ($\omega = 1$) would reduce damage in this class by two-thirds.

Specified this way, the model fails to account for damage to both larger trees (dbh > 20 cm) and seedlings and saplings (dbh < 10 cm). This is the most serious shortcoming of the model. As shown in Table 2, damage rates are high in these diameter classes, although not as high as in the 10-20 cm class. The minimum commercial log diameter in Peninsular Malaysia is on the order of 30 cm dbh, and so damage to trees with dbh > 20 cm can represent the loss of significant amounts of valuable timber. Seedlings and saplings are the trees that constitute the future forest, and so damage to trees with dbh < 10 cm diminishes the sustainability of timber harvests and environmental benefits.

The narrow definition of logging damage thus causes the simulation model to understate the economic and environmental benefits of improved logging practices. To the extent that improved practices reduce damage to potential crop trees, their adoption would in reality have a less negative impact on loggers' profits than the model predicts. This implies, for instance, that performance bonds would not need to be nearly as large in practice to induce loggers to adopt RIL as the model predicts. The omission of damage to the 0-10 cm class is especially serious. Studies other than Griffin and Caprata (1977), which provided no damage estimates for this class, indicate that it is the class that suffers the highest rate of damage (Borhan et al. 1987, Pinard and Putz 1996). Some studies suggest that significant damage to commercial-sized trees might be unavoidable even under RIL (Sist et al. 1997).

Environmental indicators

With some manipulation, predictions from the forest growth model can be used to predict the impact of logging on carbon storage and stand diversity. Carbon storage refers to the amount of carbon stored in the biomass of living trees. It includes both above-ground and below-ground biomass. It is given by

$$CS_t = \mathbf{k}\,\mathbf{y}_t, \qquad [2]$$

[2] In Indonesia, Sist et al. (1997) report that skidding is the harvesting operation mainly responsible for killing trees, while felling primarily injures trees. Injured trees do, however, experience a higher rate of mortality than trees that are not injured (Pinard and Putz 1996).

where **k** is a vector of carbon coefficients from Boscolo, Buongiorno and Panayotou (1997). In estimating the coefficients, Boscolo, Buongiorno, and Panayotou assumed that above-ground biomass is twice the mass of standing timber (Brown et al. 1989), below-ground biomass is 10 percent of above-ground biomass (Whitmore and Burnham 1984), and the carbon content of biomass is 50 percent. Table 3 shows the coefficients.

Left undisturbed, a natural forest tends to approach a steady state, generally referred to as the climax state (Ricklefs and Schluter 1993, Rosenzweig 1995). As already mentioned, the virgin forest at Pasoh is extremely diverse in terms of tree species. The level of diversity in the virgin forest provides a useful standard for measuring diversity in the logged-over forest (Boscolo and Buongiorno 1997).[3] As an operational definition of diversity, we constructed a *proximity to climax index* (PCI), equal to 1 minus the root mean squared deviation:

$$PCI_t = 1 - \sqrt{\frac{\sum_{i,j}(y_{ij0}B_j - y_{ijt}B_j)^2}{\sum_{i,j}(y_{ij0}B_j)^2}} \qquad [3]$$

B_j is the basal area of a tree in diameter class j, y_{ij0} is the number of trees in species group i and diameter class j in the virgin forest, and y_{ijt} is the corresponding number of trees t years after the initial harvest in the virgin forest. PCI equals 1 if the logged-over forest has the same structure and composition as the virgin forest, and 0 if it is clearcut. We weighted the number of trees by basal area to place more weight on the large trees that are associated with virgin conditions and, ecological studies suggest, high diversity of species other than trees.

[3] The issue of which successional stage is the most diverse in tropical forests is a matter of some disagreement. Ecologists who define diversity as the number of species per unit area tend to conclude that earlier successional stages are more diverse than mature phases. However, ecologists who define diversity as the number of species per number of individuals tend to conclude that mature phases are more diverse.

Basal area is itself a useful summary environmental indicator. It is highly correlated with biomass (thus, carbon) and crown cover (thus, protection of soil and habitat). It is also simple to measure. It is a standard variable included in forest inventories, and it can be monitored easily before and after logging. For these reasons, the simulation model also predicts total basal area,

$$BA_t = \sum_{i,j} y_{ijt} B_j \,. \qquad [4]$$

In the simulation results, we present the three indicators (CS, PCI, BA) in two forms: their value before or after logging occurs in the virgin stand (e.g., PCI_0), and the time required for the indicator to recover to within 10 percent of its value in the virgin forest, assuming no further logging occurs (e.g., T_{PCI}).[4] For example, since $PCI = 1$ in the virgin forest, T_{PCI} indicates the number of years of undisturbed forest growth for PCI in the logged-over forest to reach 0.9.

IV. THE MODEL OF LOGGER BEHAVIOR

Repeated harvesting

We model the representative logger as a forward-looking entrepreneur who, given a particular regulatory environment, attempts to maximize the net present value (NPV) of logging profits. In the absence of timber fees and other regulations, the logger's objective function for repeated harvesting is defined as

$$\mathrm{NPV} = \sum_{t=0}^{T} \sum_{i,j} \left[(P_{ij} - C_j)\, h_{ijt} - \mathrm{F_C} - \omega\, \mathrm{F_{RIL}} \right] \delta_t \,, \qquad [5]$$

where P_{ij} is the market value of the logs in a tree of species group i and diameter class j, C_j is the variable cost of felling a tree in diameter class j and transporting logs from that tree to the market

[4] We are indebted to Ken Chomitz for this suggestion.

point (a mill or port). F_C is the fixed cost of conventional logging, F_{RIL} is the additional fixed cost associated with full implementation of RIL, and δ_t is the discount factor (= $1/(1+r)^t$, where r is the discrete discount rate). The logger can choose to adopt RIL fully (ω = 1) or partially (0 < ω < 1). Note that RIL is modeled as affecting only the fixed cost of logging and that the value of ω is the same for all harvests.

According to expression [1], reduced logging damage is the sole beneficial effect of RIL in the model. In the absence of regulations, the logger's incentive to adopt RIL thus depends on the weight the logger places on the resulting increase in the future harvest of second-growth timber, which in turn depends on the logger's discount rate and the terms of the concession agreement. Regarding the former, we varied the discount rate from 1 percent to 10 percent. Regarding the latter, the logger has a private incentive to adopt RIL only in the repeated harvesting scenario, because the sequential harvesting scenario does not include second-growth harvests.

Table 4 presents the data on p_{ij} and C_j used in the model. We drew these data from ITTO and FRIM (1994). The table also shows estimates of the variable stumpage value, the difference between market value of harvested logs and the variable logging cost. Note the much higher values for dipterocarps. We set F_C equal to \$800/ha (Vincent 1990, ITTO and FRIM 1994) and F_{RIL} equal to \$135/ha (Putz and Pinard 1993).

For simplicity, we held the values of p_{ij}, C_j, F_C, and F_{RIL} constant in real terms over time. This is obviously a strong assumption. Although the average price of tropical logs in real U.S. dollars has not changed much over the past few decades (FAO 1990), many species that were noncommercial in the 1970s have since become marketable. Technological advances have tended to reduce the cost of logging in a given forest type and terrain. and fixed costs are often lower in a previously logged stand than in a virgin stand. as some logging infrastructure might already be in place. We discuss some implications of these deviations between the model and reality in the final section of this paper.

With the objective defined as above, the logger's problem is to determine when to harvest (the cutting cycle, l), which species groups and size classes to harvest ($\mathbf{h}_t$), and which logging technology to employ (ω). Mathematically, the problem is to

$$\max_{\{\mathbf{h}_t,\ \omega\}} \ \mathrm{NPV}$$

subject to

$$\mathbf{y}_{t+l} = \mathbf{G}\,[\mathbf{y}_t - \mathbf{h}_t - (1 - 2/3_{\omega})\mathbf{D}\mathbf{h}_t] + \mathbf{c}, \qquad \text{(forest growth model)}$$

$$\mathbf{h}_t,\ F_C,\ F_{RIL} \begin{cases} = 0 \ \text{if} \ t \neq k \times l \quad (k = 0, \ldots, T/l) \\ \geq 0 \ \text{if} \ t = k \times l \end{cases} \qquad \text{(harvest schedule)}$$

$$\mathbf{h}_t + (1 - 2/3_{\omega})\,\mathbf{D}\mathbf{h}_t \leq \mathbf{y}_t \qquad \text{(harvest restriction)}$$

$$\mathbf{y}_0 = \text{condition of virgin stand} \qquad \text{(initial conditions)}$$

$$\mathbf{y}_t,\ \mathbf{h}_t \geq 0 \qquad \text{(non-negativity constraints)}$$

We set the projection period (T) equal to 60 years and defined the cutting cycle (l) to the nearest decade. Hence, the set of feasible cutting cycles was 10, 20, 30, and 60 years. Sixty years is the approximate amount of time required for a seedling in Malaysian forests to develop into a timber tree with a dbh of 50-60 cm (the rotation age). k, a series of integers ranging from 0 to T/l, denotes the first, second, etc. harvest occurring during the 60-year period.

Sequential harvesting

Let π_0 denote the profit from the initial harvest in the virgin forest:

$$\pi_0 = \sum_{i,j} (P_{ij} - C_i)\, h_{ij0} - F_c - \omega\, F_{RIL}\,. \qquad [6]$$

Then the logger's NPV in the case of *unregulated* sequential harvesting is

$$\text{NPV} = \pi_0 + \pi_0/(1+r) + \ldots + \pi_0/(1+r)^S$$

$$= \pi_0 \sum_{s=0}^{S} \delta_s\,. \qquad [7]$$

We use a different index, s instead of t, to emphasize that the time increment is one year, not one felling cycle, and that with the passage of time the logger moves from one stand to another, not back to the same stand.

The only forest-related constraints that now matter to the logger are the last three from above,

$\mathbf{h}_0 + (1 - 2/3_\omega)\,\mathbf{Dh}_0 \leq \mathbf{y}_0$ (harvest restriction)

$\mathbf{y}_0$ = condition of virgin stand (initial conditions)

$\mathbf{y}_0, \mathbf{h}_0 \geq 0$ (non-negativity constraints)

The dynamics in the sequential harvesting model come entirely from the terms included in the summation sign in expression [7]. We will see shortly that these terms contain more than just discounting factors when concession renewability is linked to logging performance.

Modeling timber fees, performance bonds, and renewal conditions

Incorporating timber fees, performance bonds, and renewability criteria into the model of logger behavior is straightforward. Regarding timber fees, an *area charge* (termed a "premium" in Malaysia) of τ \$/ha changes the expression for per-hectare profits to

$$\sum_{i,j} (P_{ij} - C_j)\, h_{ijt} - F_C - \omega\, F_{RIL} - \tau \,. \qquad [8]$$

A *per-tree royalty* of τ \$/tree changes it to

$$\sum_{i,j} (P_{ij} - C_j - \tau)\, h_{ijt} - F_C - \omega\, F_{RIL} \,. \qquad [9]$$

If we redefine P_{ij}, C_j, and h_{ijt} on a cubic meter basis, then τ in this expression represents a *volume-based royalty*. Finally, an *ad valorem royalty* of τ percent of log price changes the profit expression to

$$\sum_{i,j} (\tau P_{ij} - C_j)\, h_{ijt} - F_C - \omega\, F_{RIL} \,. \qquad [10]$$

Royalties, whether per-tree, volume-based, or ad valorem, reduce the logger's profit margin on individual trees. As such, they can induce "high-grading" *within* the stand (Gillis 1980, 1992; Repetto and Gillis 1988): the failure to harvest trees of low-value species or with small diameters, because the market value of the harvested logs is less than the sum of variable logging costs and royalties. The area charge has an analogous high-grading effect *between* stands: if it is sufficiently high, it can discourage loggers from harvesting certain stands altogether, because logging revenue is inadequate to cover the sum of fixed and variable logging costs and the area charge.[5]

A *performance bond* is a mandatory deposit that the logger makes with the forestry department before logging. If the logger complies with all applicable regulations, then the department reimburses him the full amount of the deposit. If the logger fails to comply with certain regulations, however, the department keeps some or all of the deposit

[5] Royalties can also induce high-grading between stands.

The Peninsular Malaysia Forestry Department does not currently use performance bonds, but in principle it and other forestry departments in tropical countries could use bonds to promote better logging practices. The Philippines has in fact experimented with their use (Paris, Ruzicka, and Speechly 1994). In the simulation model, if the forestry department wished to encourage loggers to adopt RIL, it could levy a bond of \$PB per hectare and make reimbursement proportional to ω. This would change the profit per harvest to

$$\sum_{i,j} (P_{ij} - C_j)h_{ijt} - \mathrm{F_C} - \omega \mathrm{F_{RIL}} - (1-\omega)\mathrm{PB},$$

or

$$\sum_{i,j} (P_{ij} - C_j)h_{ijt} - \mathrm{F_C} - \mathrm{PB} + \omega(\mathrm{PB} - \mathrm{F_{RIL}}). \qquad [11]$$

The effect is to reduce the cost of RIL to the logger from PB to PB $-$ $\mathrm{F_{RIL}}$.

Similarly, if the department wished to encourage the logger to comply with a minimum diameter cutting limit of, say, 60 cm, it could require a bond of

$$\mathrm{UPB} \sum_{i,j} y_{ijt},$$

where i includes only commercial species (the species that tempt the logger to violate the cutting limit), and j ranges from dbh =30 cm (the minimum commercial log diameter) to dbh=60 cm (the prescribed cutting limit). $\sum y_{ijt}$ is thus the number of trees of commercial species below the cutting limit. UPB, the unit performance bond, is in effect the "price" the department charges for harvesting a commercial tree below the cutting limit. The logger can avoid paying this price by not violating the limit, in which case he is reimbursed the full amount of the deposit. The inclusion of this type of performance bond alters the profit per harvest to

$$\sum_{i,j} (P_{ij} - C_j)h_{ijt} - F_C - \omega F_{RIL} - UPB \sum_{i,j} (y_{ijt} - y'_{ijt}) , \qquad [12]$$

where y_{ijt} is the number of commercial trees below the cutting limit before the harvest and y'_{ijt} is the remaining number after the harvest.

In practice, performance bonds should be linked to variables that are easy to monitor and verify, in order to reduce implementation costs and potential disagreements about the level of reimbursement. Determining whether a logger has adopted RIL might require costly, extended site visits during all stages of the logging operation.[6] Few forestry departments in developing countries have enough personnel to do such intensive monitoring. Determining whether loggers have complied with minimum diameter cutting limits is likely to be easier, particularly in countries like Malaysia that conduct inventories of logging compartments before and after felling. Inventory data offer a direct, performance-based indicator of compliance with cutting limits that does not have an obvious parallel in the case of RIL.

Linking *renewal* of the concession agreement to logger performance offers more leverage over logger behavior in the sequential harvesting scenario, for the simple reason that the benefits of renewal to the logger (i.e., profits from future harvests) are not discounted as many years as in the repeated harvesting scenario. Linking the probability of renewal to adoption of RIL changes the logger's objective function under sequential harvesting to

$$\pi_0 \sum_{s=0}^{S} [\omega/(1+r)]^s . \qquad [13]$$

[6] This might not necessarily be the case in all situations. For example, two critical elements that characterize RIL, forest mapping and planning of roads and skid trails, could be verified by reviewing logging plans and making a site visit to check that the plans have been implemented.

s can be interpreted as the number of times a one-year agreement can be renewed. Similarly, linking the probability of renewal to compliance with minimum diameter cutting limits changes the objective function to

$$\pi_0 \sum_{s=0}^{S} [(\sum_{i,j} y'_{ij0} / \sum_{i,j} y_{ij0}) / (1+r)]^s, \qquad [14]$$

where, as in [12], j runs from the minimum commercial log diameter to the cutting limit.

Interpretation of results for simulations involving [12] is made somewhat easier by linking the bond to *timber volume* below the cutting limit instead of number of trees below the limit. Then, UPB is expressed in $/m^3, the same units as the volume-based royalty. We report estimates of UPB in this form below.

V. RESULTS: REPEATED HARVESTING

For the case of repeated harvesting, we analyzed three sets of regulatory scenarios: no regulations, royalties but no performance bonds, and performance bonds with and without royalties.

No regulations

This scenario ignores timber fees and all other regulations, including minimum diameter cutting limits. It is equivalent to the logger having a 60-year, unconditional, nonrenewable lease. At a 10 percent discount rate, the profit-maximizing solution is to harvest twice, at the beginning and the end of the period (i.e., in years 0 and 60). The harvest intensity is at the maximum: the logger harvests all the available dipterocarps and commercial nondipterocarps with dbh $\geq$ 30 cm at each harvest. He extracts 74 m^3/ha during the first harvest and 30 m^3/ha during the second.

He does so using conventional logging techniques. We refer to this simulation as the baseline simulation.

The logger's behavior in this simulation is at odds with logging regulations in Peninsular Malaysia, which prescribe minimum diameter cutting limits of 50-60 cm and a cutting cycle of around 30 years for most forests. The simulation results can be viewed either as confirming a fundamental regulatory challenge facing the Peninsular Malaysia Forestry Department, for loggers do indeed harvest all commercial trees when permitted to do so (e.g., during land conversion), or as raising doubts about setting cutting limits so far above the minimum commercial log diameter. We will return to the latter point at the end of this section.

Table 5 presents the simulation details. The NPV is \$4402/ha, which comes almost entirely from the first harvest (\$4398/ha). The profit of \$1136/ha from the second harvest contributes little to the NPV, because of discounting. After the first harvest, the stand's aggregate stumpage value is negative until year 35. A lower fixed cost for harvests after the first would make the stumpage value positive sooner and, if the reduction were large enough, would make the profit-maximizing cutting cycle 30 years instead of 60 years.[7]

The use of conventional logging techniques results in high rates of damage to trees in the 10-20 cm dbh class: 60.9 percent during the first harvest and 23.2 percent during the second. Had the model also included damage to trees of commercial diameter, both harvests would have been reduced by 20-40 percent, according to estimates in Griffin and Caprata (1977; see Table 2). For this reason, the NPV predicted by the model overstates the NPV of actual logging operations.

The high rates of damage, combined with the heavy harvesting, reduce all environmental indicators significantly: BA is 60 percent lower immediately after the first harvest, CS is 64 percent lower, and PCI is 74 percent lower. If the stand is left undisturbed after year 60, the indicators recover, but at different rates (see Figures 2 and 3). BA and CS recover most quickly, reaching 90 percent of their virgin values (i.e., T_{BA} and T_{CS}) in 57 years and 43 years, respectively. After about a century, they level off at values comparable to those in the virgin stand (see Figure 2). PCI takes much longer to recover 90 percent of the virgin value (T_{PCI}), 129 years. Even after one and a half centuries, it is still more than 5 percent below the virgin value and appears to have leveled off, thus suggesting a permanent loss of diversity. Had the model

[7] Recall that we limited the choice of cutting cycles to 10, 20, 30, and 60 years.

included damage to trees in the 0-10 cm and 20-30 cm dbh classes, values of all indicators would have been lower, and recovery times would have been longer.

Changing the discount rate from 10 percent to 5 percent had no effect on harvest timing, harvest intensity, logging technology, or, consequently, the environmental indicators. This reflects the fact that trees above 30 cm dbh appreciate in value terms by less than 5 percent per year. Hence, from a private standpoint, it is not economically desirable to leave them to grow in the forest, even at a discount rate as low as 5 percent. Harvest intensity changed only when we reduced the discount rate to 1 percent. Then, the profit-maximizing solution involved leaving some dipterocarps of commercial size standing in the forest until the second harvest. All other commercial species above 30 cm were still harvested. The reduction in the discount rate did not affect harvest timing (still two harvests, in years 0 and 60) or logging technology (conventional logging was still preferred).

The most important policy implication of these results is that converting concessions from short-term harvest licenses to longer term agreements, to enable loggers to harvest the same stand again in the future, is unlikely to induce loggers to adopt RIL or to comply with minimum diameter cutting limits. Additional regulations are required to achieve these objectives.

Royalties

Although royalty-induced high-grading is often described as a "problem" in the literature on tropical timber concessions, it might not be undesirable when a forestry department wishes to discourage loggers from violating minimum diameter cutting limits. Table 6 shows "threshold" values for the three royalties: the highest values (to the nearest \$5 or 5 percent) they can have without inducing high-grading. The volume-based royalty had no impact on logging decisions for values up to \$35/m^3: the logger continued to harvest all trees of commercial species with dbh

$\geq$ 30 cm, using conventional logging techniques, in years 0 and 60. Only when the royalty exceeded this level (results not shown) did it affect harvest intensity, causing the logger to forgo harvesting some medium-sized commercial nondipterocarps. However, the logger still preferred conventional logging. At even higher levels, fewer and fewer trees were harvested. For example, at $60/m^3, only dipterocarps above 40 cm were harvested.

Because an increase in the volume-based royalty has the same impact on the logger's profit function as an identical increase in the variable logging cost, these results can also be interpreted as indicating the effect of transportation costs on logging decisions. Anecdotal evidence from various countries indicates that harvests do indeed tend to be less intensive in forests that are further from a mill or port. For an example from Bolivia, see Rice et al. (1997). By lowering transportation costs, the construction of new and improved roads can be expected to increase the extraction of less valuable species and smaller diameter classes.

Table 6 shows that logging profit is positive for both harvests at the $35/m^3 royalty. For royalties of $50/m^3 and higher, however, the profit for the second harvest is below zero. This indicates that the profit-maximizing cutting cycle is longer than 60 years: the logger will not harvest until the trees are even larger and more valuable. The introduction of the royalty thus tends to lengthen the cutting cycle.[8] It also tends to discourage the adoption of RIL. As mentioned earlier, RIL benefits the logger by reducing logging damage and thereby raising future stocks of harvestable timber. Higher royalties reduce the profits from future harvests and thus reduce the financial incentive to adopt RIL. Hence, it is not surprising that conventional logging remains the preferred logging technology in all the royalty simulations.

[8] This is a standard forest economics result.

The per-tree royalty works even more directly as a disincentive against violating minimum diameter cutting limits. High-grading began once the royalty exceeded $20/tree. At $50/tree, the logger did not harvest dipterocarps below 40 cm dbh and other commercial species below 50 cm dbh.

The ad valorem royalty induced high-grading only if it exceeded 65 percent, but at this high level it made logging unprofitable during the second harvest. This result illustrates that the royalties affect the allocation of stumpage value between the logger and the government in different ways. For a given amount of high-grading, the per-tree royalty generates the least government revenue, and the ad valorem royalty generates the most.[9] During the first harvest, the $20 per-tree royalty generates only a third as much revenue as the $35/m^3 volume-based royalty and a fifth as much as the 65 percent ad valorem royalty.

We did not run specific simulations for the area charge, as its effects are clear from inspecting expression [8]. Its maximum value is determined by the logging profit per harvest. Thus, for example, in the absence of royalties the forestry department could levy an area charge up to $4398/ha for the first harvest and $1136/ha for the second (Table 5). Higher values would destroy the financial viability of logging. Because the area charge is levied on a per-hectare basis, it does not affect marginal logging decisions. It therefore cannot be used to discourage violations of minimum diameter cutting limits. But by reducing profits from future harvests, it does discourage the adoption of RIL.

Performance bonds

[9] This again is a standard result. See Gillis (1980, 1992) and Repetto and Gillis (1988).

In contrast to timber fees, performance bonds can be used to induce the logger both to adopt RIL and to comply with minimum diameter cutting limits. When the discount rate is high and the cutting cycle is decades-long, the benefit to the logger of adopting RIL—i.e., the present value of increased profits from higher future harvests—is negligible. Then, the impact of the performance bond on adoption of RIL can be analyzed by considering expression [11] applied to just the initial harvest in the virgin forest. There is no need to run simulations. From inspecting the expression, it is obvious that the bond, PB, must just marginally exceed the incremental cost of RIL, F_{RIL} (= \$135/ha), to induce the logger to adopt RIL. If instead the benefit of RIL to the logger is not negligible (e.g., if the logger's discount rate is very low), then the value of PB that induces the adoption of RIL can be less than F_{RIL}.

The bond must be considerably higher to induce compliance with the minimum diameter cutting limits. In the simulations, the value of UPB in expression [12] ranged from \$55/m^3 for a cutting limit of 40 cm, to \$70/m^3 for 50 cm and \$85/m^3 for 60 cm. Table 7 shows these and additional results. The corresponding performance bonds (= UPB $\sum y_{ijt}$) were \$492/ha, \$1241/ha, and \$2386/ha, respectively. The UPBs and performance bonds are so high because of the substantial timber values below the cutting limits. They increase with the cutting limit because stumpage values are higher for larger diameter trees (Table 4), and thus a larger "penalty" is needed to discourage the logger from violating the limit. Such high deposits — up to three times the fixed cost of conventional logging — could well be infeasible in developing countries with poorly developed credit markets.

In those situations, the use of performance bonds might need to be limited to inducing the adoption of RIL. But as noted earlier, linking a performance bond to ω is likely to be more difficult in practice than linking it to timber volumes. Is there any way to design a bond linked to timber volumes that induces the logger to adopt RIL? At first glance, the simulation results in Table 7 suggest that the answer is no: even at the very high UPB values in the table, the logger still selects conventional logging. This result is not surprising: the difference between y_{ijt} and y'_{ijt} in expression [12] is the amount of timber below the cutting limit that the logger harvests, and so UPB is behaving just like a royalty.

If, however, we redefine the lower limit of j in the performance bond portion of expression [12] from 30 cm dbh (the minimum commercial log diameter) to 10 cm dbh (the lower limit of the diameter classes that suffer logging damage), then a single bond based on timber volume below the cutting limit can achieve both objectives. Table 8 shows the simulation results. A bond of $51/m³ induces compliance with the 40 cm cutting limit. This is less than the $55/m³ when the lower limit of j is 30 cm (in Table 7), because violating the limit and felling the 30-40 diameter class is now associated with foregoing both the reimbursement of the bond deposited for both the 30-40 cm class and for the damage to the 10-20 cm class.

Raising the bond only slightly, from $51/m³ to $56/m³, induces the adoption of RIL. The incremental cost of the bond to the logger, $5/m³ times the timber volume in the 10-40 cm dbh classes (18.9 m3/ha), is smaller than the incremental cost of RIL ($135/ha). The reason is that the logger now reaps an immediate benefit from RIL: by damaging less timber in the 10-20 cm class, he recovers more of the bond. Increasing the bond further induces compliance with 50 cm and then 60 cm cutting limits, while maintaining the incentive to adopt RIL. On a per hectare basis, the bonds for these cutting limits are very large, $1906-3432/ha, but the logger is reimbursed nearly the full value of the bond.

Environmental indicators

Figures 4-6 show the environmental benefits, in non-monetary terms, of RIL and the cutting limits. They show how the environmental indicators recover after the initial logging in the virgin forest, assuming no further logging occurs. The figures for BA and CS are similar. In both cases, RIL provides relatively larger environmental benefits than the cutting limits. For example, the adoption of RIL raises carbon storage immediately after logging by approximately 50 tons/ha, from about 80 tons/ha under conventional logging to just under 130 tons/ha for RIL. Compliance with the cutting limits raises carbon storage further, but by lesser amounts. The difference between RIL with no cutting limit (just under 130 tons/ha) and RIL with the highest cutting limit (just over 160 tons/ha) is not much more than 30 tons/ha.

The values of BA and CS in the different regulatory scenarios converge after about 100 years. As they do, the relative gaps between them remain about the same. The trends for PCI are different. The initial impacts of RIL and cutting limits on this indicator are similar to those for BA and CS: the adoption of RIL raises PCI by about 0.20, while compliance with the 60 cm cutting limit raises it by less than another 0.1. But the gap between the values of PCI for RIL with no cutting limit and conventional logging closes within 50 years after logging, much sooner than in the case of BA and CS. Why? Recall that the sole ecological impact of RIL in the model is to reduce logging damage in the 10-20 cm class. Adoption of RIL causes a larger number of trees to be retained in this class. In the absence of cutting limits, this has a relatively large initial impact on PCI, because all trees of commercial species above 30 cm are removed. But this impact is diluted as time passes and recruitment into the 0-10 cm class, which is not affected by RIL, occurs. Figures 4 and 5 do not show as rapid convergence for BA and CS because these indicators are, in contrast to PCI, simple sums across all diameter classes. The distribution of trees across diameter classes affects PCI, but not BA and CS.

The environmental benefits generated by adoption of RIL and compliance with minimum diameter cutting limits come at a cost, namely a loss in timber value. The last column of Table 8 shows that, at a 10 percent discount rate, the sum of the logger's NPV and the present value of government revenue is 40 percent lower ($1743/ha) under the "environmentally friendly" combination of RIL and a 60 cm cutting limit than under unregulated conventional logging. The cutting limit is responsible for most of the loss: it prevents the logger from harvesting all the trees that are financially mature at the time of the initial harvest. The question from an economic standpoint is whether the incremental environmental benefits associated with minimum diameter cutting limits are worth the loss of so much timber value. We cannot answer this question, as we did not attempt to value the benefits associated with higher levels of BA, CS, and PCI. We can conclude, however, that minimum diameter cutting limits are not justified on the basis of timber values alone.[10]

VI. RESULTS: SEQUENTIAL HARVESTING

No regulations

In the baseline case for sequential harvesting (no regulations), the logger's behavior is exactly the same as during the initial harvest in the baseline case for repeated harvesting (Table 5): the logger harvests all trees of commercial species and sizes using conventional logging. Lengthening the agreement (raising S) has no impact on behavior, nor does lowering the logger's discount rate. As noted earlier, the logger has no incentive whatsoever to adopt RIL under

[10] Some tropical foresters have also questioned the silvicultural basis for minimum diameter cutting limits in dipterocarp forests, noting that seedlings of the commercially most desirable dipterocarp species are light-demanding and thus grow more vigorously if more of the canopy is removed. See Appanah and Weinland (1990).

sequential harvesting. With no prospect of a harvest in the second-growth forest, the logger likewise has no incentive to retain small-diameter commercial trees in the forest to grow, even at a discount rate of zero.

Performance-based renewal, performance bonds, and timber fees

Making the probability of renewal of the concession agreement proportional to ω, as in expression [13], is on its own sufficient to induce the logger to adopt RIL. This is true even when renewal is for just one additional year, that is when $\varsigma = 1$: a two-year agreement, with renewal for the second year contingent on performance during the first year. The profit from harvesting a new virgin stand is so great that the logger is more than willing to secure the opportunity by incurring the extra $135/ha in fixed logging costs associated with RIL.

For similar reasons, the introduction of performance-based renewal conditions reduces the size of performance bonds required to induce compliance with minimum diameter cutting limits. Table 9 summarizes the results of simulations in which the performance bond was linked, as in [14], to the volume of timber in trees of commercial species with dbh between the minimum commercial log diameter (i.e., 30 cm, not 10 cm) and the minimum diameter cutting limits. In the absence of timber fees and with no prospect of renewal ($\varsigma = 0$), the UPB had to be $85/m^3 to induce compliance with a minimum diameter cutting limit of 60 cm, $70/m^3 for 50 cm, and $55/m^3 for 40 cm—the same as in Table 7 for repeated harvesting. The values actually differ slightly, due to the fact that the repeated harvesting model includes future harvests in the second-growth forest, but at a 10 percent discount rate the differences are negligible.

Setting $\varsigma = 1$—just one renewal year — caused the UPB for the 60 cm cutting limit to drop by more than half, to $38/m^3. For the 50 cm and 40 cm cutting limits, no bond was required at all (UPB = 0): the performance-based renewal condition was adequate to induce compliance on its own. Extending the agreement to $\varsigma = 2$ made the renewal condition adequate on its own for even the 60 cm cutting limit.

We analyzed interactions among renewal conditions, performance bonds, and timber fees for three fees: an area charge, a volume-based royalty, and an ad valorem royalty. We set the fees at levels that generated identical amounts of government revenue when other regulations, including renewal conditions, were absent. Results for the area charge (= \$1479/ha) were identical to results for the case of no fees. The introduction of royalties, however, reduced the UPB, especially for $\varsigma = 0$. With no possibility of renewal, the volume-based royalty (= \$20/m^3) reduced the UPB for the 60 cm cutting limit from \$85/m^3 to \$65/m^3, while the ad valorem royalty (= 23 percent of log price) reduced it slightly more, to \$62/m^3. Differences in the high-grading effects of the two royalties reversed the relative impact in the case of the 40 cm cutting limit, as the volume-based royalty generated the larger reduction (to \$35/m^3 vs. \$38/m^3).

Introducing renewal conditions as in [14], with $\varsigma = 1$, diminished the impact of the royalties on the UPB for the 60 cm cutting limit. The UPB fell from \$38/m^3 in the absence of fees, to \$34/m^3 in the presence of the volume-based royalty and \$32/m^3 in the presence of the ad valorem royalty.

VII. CONCLUSIONS

The principal conclusions of this study can be summarized as follows:

1. Due to the effects of discounting, longer concessions provide little incentive for loggers to adopt RIL or to comply with minimum diameter cutting limits.

2. Royalties can be used to encourage compliance with minimum diameter cutting limits, but they discourage adoption of RIL. The types of royalties that are more effective in encouraging compliance with minimum diameter cutting limits (e.g., per-tree royalties) tend to be less effective as revenue instruments.
3. Relatively small performance bonds can be used to induce loggers to adopt RIL, but very large bonds are needed to induce compliance with minimum diameter cutting limits.
4. RIL and minimum diameter cutting limits both have significant, positive impacts on environmental indicators related to carbon storage and biodiversity. In the case of minimum diameter cutting limits, however, the environmental benefits are obtained at the cost of a substantial reduction in the timber value of the stand.
5. Performance-based renewal conditions provide a powerful incentive for loggers to adopt RIL and to comply with minimum diameter cutting limits. This is the case even when concession agreements are very short (only 1-2 renewal years).
6. Performance-based renewal conditions sharply reduce the size of the performance bond needed to induce compliance with minimum diameter cutting limits. Royalties, but not area charges, have a similar, though weaker, effect.

Most of the simulation results reported in this paper indicate that loggers prefer longer, rather than shorter, cutting cycles. On the surface, this appears to be inconsistent with anecdotal evidence about loggers' behavior in many tropical countries: that they harvest the logged-over forest sooner than the prescribed cutting cycle. This is the issue of premature reentry. But note that the simulation model predicts that long cutting cycles are preferrred *when the logger is permitted to harvest intensively during the initial harvest*. When this is not the case—for example, when we impose regulations that induce compliance with minimum diameter cutting limits (Tables 7 and 8)—the model predicts shorter cutting cycles. This simply confirms that commercial-sized timber left standing in the forest tempts the logger to reenter the forest to harvest it, as it is already financially mature.

This temptation is heightened if log prices rise, transportation costs fall, or more species become marketable—all of which have occurred in Peninsular Malaysia since the early 1970s. It is also heightened if, contrary to the assumptions of the simulation model, fixed logging costs are lower in logged-over forests than in the virgin forest. To investigate these issues, we ran a simulation without timber fees or performance bonds in which the fixed logging cost fell from $800/ha at the first harvest to $400/ha for subsequent harvests and the minimum diameter cutting limit was enforced only for the first harvest. The logger's profit-maximizing decision under these conditions was to extract 46 m^3/ha during the initial harvest, thus earning a profit of $2766/ha, and then to reenter the stand in 10 years, to extract an additional 34 m^3/ha and to earn an additional profit of $1700/ha. That is, the decision mirrored the premature reentry behavior observed in tropical forests. This result suggests that minimum diameter cutting limits that exceed minimum commercial log diameters, when combined with weak control over access to logged-over forests, are a principal cause of premature reentry.

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Appendix I: The forest growth model

In the model developed by Boscolo et al. (1997), the structure of the forest stand is represented by the vector $\mathbf{y}_t = [y_{i,j,t}]$, where $y_{i,j,t}$ is the number of trees per hectare of species group i ($i = 1, \ldots, m$) in diameter class j ($j = 1, \ldots, n$) at time t. The harvest at time t is given by the vector $\mathbf{h}_t = [h_{i,j,t}]$. Changes in stand structure over time are determined by a system of dynamic equations,

$$y_{i,1,t+1} = (y_{i,1,t} - h_{i,1,t})\, a_{i,1} + I_i$$

$$y_{i,2,t+1} = (y_{i,1,t} - h_{i,1,t})\, b_{i,2} + (y_{i,2,t} - h_{i,2,t})\, a_{i,2}$$

$$y_{i,3,t+1} = (y_{i,2,t} - h_{i,2,t})\, b_{i,3} + (y_{i,3,t} - h_{i,3,t})\, a_{i,3}$$

....

$$y_{i,n,t} = (y_{i,n-1,t} - h_{i,n-1,t})\, b_{i,n} + y_{i,n,t}\, a_{i,n}, \qquad (1)$$

where $a_{i,j}$ is the probability that a live tree in diameter class j at time t will still be alive and in that class at time $t+1$, $b_{i,j}$ is the probability that a live tree in diameter class $j-1$ at time t will move up to class j at time $t+1$, and I_i is recruitment, or ingrowth (the number of trees that enter the smallest diameter class between t and $t+1$). As indicated, the model assumes that the transition probabilities (the parameters $a_{i,j}$ and $b_{i,j}$) are independent of stand state, but it assumes that ingrowth depends on stand density and composition. Ingrowth for a given species group is a positive function of the number of trees of that species present in the stand (and thus providing seed) and a negative function of total basal area of the stand (which captures the effect of competition):

$$I_{i,t} = \alpha_i + \beta_i \sum_{i=1}^{m} \sum_{j=1}^{n} B_j (y_{i,j,t} - h_{i,j,t}) + \gamma_i \sum_{j=1}^{n} (y_{i,j,t} - h_{i,j,t}), \qquad (2)$$

where B_j is the basal area of a tree in diameter class j.

In matrix form, the model is formulated as (Buongiorno and Michie 1980)

$$\mathbf{y}_{t+1} = \mathbf{G}(\mathbf{y}_t - \mathbf{h}_t) + \mathbf{c}, \tag{3}$$

where

$$\mathbf{G} = \begin{bmatrix} \mathbf{G}_1 & & & \\ & \mathbf{G}_2 & & \\ & & \cdots & \\ & & & \mathbf{G}_m \end{bmatrix} \qquad \mathbf{c} = \begin{bmatrix} \mathbf{c}_1 \\ \mathbf{c}_2 \\ \cdots \\ \mathbf{c}_m \end{bmatrix}$$

and

$$\mathbf{G}_i = \begin{bmatrix} a_1 & & & \\ b_2 & a_2 & & \\ & \cdots & \cdots & \\ & & b_n & a_n \end{bmatrix} \qquad \mathbf{c}_i = \begin{bmatrix} I_i \\ 0 \\ \cdots \\ 0 \end{bmatrix}$$

Transition probabilities are usually estimated, straightforwardly, as the proportions of trees that stay in the same diameter class or move up to the next one during a given time interval (method I of Michie and Buongiorno 1984). This method has been applied extensively (see Mendoza and Setyarso 1986, Osho 1991). When applied to the Pasoh dataset, however, it generated steady-states that were unrealistic. For example, some diameter classes had a negative number of trees. Boscolo et al. (1997) addressed this problem by using an approach similar to one used by Ingram and Buongiorno (1996) for a lowland tropical forest in Malaysia and Houde and Ledoux (1995) for natural forest stands in Guyana. They assumed that the upgrowth parameters (the $b_{i,j}$s) from the Pasoh censuses were representative of long-term values, while mortality rates (which affect the $a_{i,j}$s) were below long-run values. These are reasonable assumptions, as: (i) diameter growth can be estimated more accurately than mortality, (ii) growth rates based on the Pasoh date are consistent with ones from other growth and yield studies in Peninsular Malaysia, and (iii) windstorms, which occur occasionally in the vicinity of Pasoh and represent a source of catastrophic mortality, did not occur between the two censuses. If a further assumption is made that the plot is in a steady state (i.e.. at its ecological climax), then the $a_{i,j}$s can be estimated from the equations,

$$a_{i,1} = -(I_i^s - y_{i,1}^s)/y_{i,1}^s$$

$$a_{i,2} = (y_{i,2}^s - y_{i,1}^s\, b_{i,2})/\, y_{i,2}^s$$

.....

$$a_{i,n} = (y_{i,n}^s - y_{i,n-1}^s\, b_{i,n})/\, y_{i,n}^s \tag{4}$$

which imply mortality rates of $m_{i,j} = 1 - a_{i,j} - b_{i,j+1}$. Table A.1 shows the final transition probabilities used in the matrix model.

The transition probabilities are independent of stand state under this approach, but ingrowth is not. To estimate the effects of stand density and composition on ingrowth (equation (2)), the plot was divided into 50 subplots of one hectare each. Table A.2 shows estimation results for the ingrowth equations. All coefficients had the expected signs: i.e., ingrowth in each species group was influenced positively by the number of trees in that group and negatively by total basal area. The coefficients of determination varied between 0.9 and 0.32, so the model did not explain most of the variability in ingrowth. The coefficients on the independent variables were, however, statistically significant at the 5% level in all three equations.

Table 1. Structure of an average hectare in the virgin forest.

Diameter class (cm)	Trees (no.)				Basal area (m^2)				Net volume* (m^3)			
	D	O	N	Total	D	O	N	Total	D	O	N	Total
10-20	30.5	61.5	262.3	354.2	0.5	1.1	4.6	6.3	1.7	3.5	15.0	20.2
20-30	11.6	17.5	61.5	90.7	0.6	0.9	3.0	4.5	1.9	2.8	9.8	14.5
30-40	5.4	8.9	19.8	34.1	0.5	0.9	1.9	3.3	3.4	5.6	12.4	21.3
40-50	3.9	4.6	7.2	15.8	0.6	0.7	1.1	2.5	4.0	4.8	7.4	16.3
50-60	3.6	3.1	2.9	9.5	0.9	0.7	0.7	2.3	5.6	4.8	4.5	14.7
60-70	2.5	1.7	0.9	5.2	0.8	0.6	0.3	1.7	8.1	5.5	2.9	16.8
70+	5.9	1.6	0.9	8.4	3.0	0.8	0.5	4.2	25.4	6.9	3.9	36.2
Total	63.5	98.9	355.4	517.8	6.9	5.6	12.1	24.7	50.1	33.8	55.9	140.0

D = dipterocarp, O = other commercial species, N = noncommercial species.

* Timber volume net of defect.

Table 2. Estimates of logging damage rates from selected studies.

Conventional logging	RIL	Damage definition	Source
48.4%	30.5%	Injured or killed, dbh ≥ 10 cm*	Sist et al. (1997)
17-57%	2-22%	Killed, 1-60 cm	Pinard and Putz (1996)
3.5-10%	3.5-10%	Injured (snapped-off)	
41%	15%	Killed, 5-60 cm.*	Pinard et al. (1995)
20%		≥ 60 cm	Griffin and Caprata (1977)
30%		45-59.9 cm	
40%		30-44.9 cm	
50%		15-29.9 cm	
69%		15-30 cm	Canonizado (1978, cited in Appanah and Weinland, 1990)
64%		30-50 cm	
8-21%**		Stem and crown damage; unclear if killed trees included	Borhan et al. (1987)

* Undifferentiated by size class.
** Using tractor/skidder for hauling.

Table 3. Estimates of carbon storage per tree (above-ground and below-ground biomass combined).

dbh (cm)	Carbon storage (tons/tree)		
	D	O	N
10-20	0.24	0.24	0.27
20-30	0.32	0.32	0.35
30-40	0.60	0.60	0.66
40-50	0.86	0.85	0.94
50-60	1.17	1.15	1.28
60-70	2.58	2.54	2.83
70+	3.54	3.49	3.88

D = dipterocarp, O = other commercial species, N = noncommercial species.

Source: Boscolo and Buongiorno (1997).

Table 4. Estimates of log prices, variable logging costs, and stumpage values per tree (1991 prices).

dbh (cm)	Net volume (m^3/tree)	Ex-mill log price ($/tree)			Variable logging cost ($/tree)			Stumpage value ($/tree)		
		D	O	N	D	O	N	D	O	N
15	0.057	0	0	0	0	0	0	0	0	0
25	0.160	0	0	0	0	0	0	0	0	0
35	0.625	45	33	0	-11	-11	-1	34	22	-1
45	1.034	90	66	0	-18	-18	-2	72	48	-2
55	1.544	157	116	0	-26	-26	-3	131	90	-3
65	3.235	330	243	0	-55	-55	-6	275	188	-6
75	4.307	439	323	0	-73	-73	-9	366	250	-9

D = dipterocarp, O = other commercial species, N = noncommercial species.

Sources: Volume equations from Awang Noor, Vincent, and Hadi (1992); average prices and logging costs from ITTO and FRIM (1994). Logging costs include transportation costs. Ratio of fixed costs to total costs from Vincent (1990). Fixed costs are estimated at $800/ha, which assumes an average harvest of $50m^3$/ha. Variable costs are estimated at $17/$m^3$.

Table 5. Repeated harvesting: logging behavior in the absence of regulations (10 percent discount rate).

Year	Aggregate stumpage value ($/ha)	Logging profit ($/ha)	Harvest volume (m^3/ha)	Logging damage (%)	*BA* before logging (m^2/ha)	*BA* after logging (m^2/ha)	*CS* before logging (tons/ha)	*CS* after logging (tons/ha)	*PCI* before logging	*PCI* after logging
0	4398	4398	74	60.9	24.7	10.1	214	77	1.00	0.26
5	-690	0	0	0.0	10.9	-	92	-	0.34	-
10	-572	0	0	0.0	11.8	-	106	-	0.40	-
15	-470	0	0	0.0	12.7	-	118	-	0.44	-
20	-348	0	0	0.0	13.6	-	130	-	0.47	-
25	-213	0	0	0.0	14.5	-	140	-	0.50	-
30	-63	0	0	0.0	15.4	-	149	-	0.52	-
35	103	0	0	0.0	16.3	-	158	-	0.53	-
40	285	0	0	0.0	17.1	-	166	-	0.54	-
45	480	0	0	0.0	17.9	-	173	-	0.56	-
50	689	0	0	0.0	18.7	-	179	-	0.57	-
55	908	0	0	0.0	19.5	-	185	-	0.58	-
60	1136	1136	30.3	23.2	20.2	13.7	190	132	0.60	0.46

BA = basal area.
CS = carbon storage.
PCI = Proximity to climax index.

Table 6. Repeated harvesting: logging behavior in the presence of royalties (10 percent discount rate). The indicated values for the royalties are the highest values that do not induce high-grading.

Royalty	Solution	Logging profit ($/ha)		Government revenue ($/ha)	
		Year 0	Year 60	Year 0	Year 60
None	Harvest D ≥ 30 cm dbh Harvest O ≥ 30 cm dbh Conventional logging 60-year felling cycle	4398	1136	0	0
Volume-based: $35/m3	Same as above	1809	74	2589	1062
Per tree: $20/tree	Same as above	3574	587	824	548
Ad valorem: 65% of log price	Same as above	198	- 463	4200	1598

Table 7. Repeated harvesting: logging behavior in the presence of performance bonds, I (10 percent discount rate).

Performance bond ($/m$^3_{30\text{-lim}}$)*	Logging behavior	Logging profit ($/ha)			Government revenue** ($/ha)			NPV ($/ha)
		Year 0	Year 30	Year 60	Year 0	Year 30	Year 60	
None	Cut D ≥ 30 cm dbh Cut O ≥ 30 cm dbh Conventional logging	4398	0	1136	0	0	0	4402
55	Cut D ≥ 40 cm dbh Cut O ≥ 40 cm dbh Conventional logging	4019	184	239	0 (492)	0 (438)	0 (504)	4030
70	Cut D ≥ 50 cm dbh Cut O ≥ 50 cm dbh Conventional logging	3517	352	328	0 (1241)	0 (1147)	0 (1241)	3538
85	Cut D ≥ 60 cm dbh Cut O ≥ 60 cm dbh Conventional logging	2766	596	547	0 (2386)	0 (2268)	0 (2318)	2802

* The bond is linked to the net timber volume in trees of commercial species with 30 cm ≤ dbh ≤ minimum diameter cutting limit.
** The per-hectare value of the bond is given in parenthesis. The amount reimbursed is the difference between the figure in parenthesis and the figure immediately above.

Table 8. Repeated harvesting: logging behavior in the presence of performance bonds, II (10 percent discount rate).

Performance bond ($\$/m^3_{10\text{-lim}}$)*	Logging behavior	Logging profit ($/ha)			Government revenue** ($/ha)			NPV ($/ha)
		Year 0	Year 30	Year 60	Year 0	Year 30	Year 60	
None	Cut D ≥ 30 cm dbh Cut O ≥ 30 cm dbh Conventional logging	4398	0	1136	0	0	0	4402
51	Cut D ≥ 40 cm dbh Cut O ≥ 40 cm dbh Conventional logging	3831	142	195	188 (961)	42 (912)	43 (1078)	4030
56	Cut D ≥ 40 cm dbh Cut O ≥ 40 cm dbh RIL	3815	103	207	69 (1055)	16 (1130)	18 (1259)	3892
69	Cut D ≥ 50 cm dbh Cut O ≥ 50 cm dbh RIL	3389	225	275	73 (1906)	20 (1989)	20 (2170)	3477
84	Cut D ≥ 60 cm dbh Cut O ≥ 60 cm dbh RIL	2558	439	445	73 (3190)	29 (3255)	30 (3432)	2659

* The bond is linked to the net timber volume in trees of commercial species with 10 cm ≤ dbh ≤ minimum diameter cutting limit.
** The per-hectare value of the bond is given in parenthesis. The amount reimbursed is the difference between the figure in parenthesis and the figure immediately above.

Table 9. Sequential harvesting: logging behavior in the presence of performance-based renewal conditions, performance bonds, and royalties (10 percent discount rate).

Number of renewal years (S)	Timber fees	Bond ($\$/m^3$) required to induce compliance with cutting limit of:		
		60 cm	50 cm	40 cm
0	None	85	70	55
1	None	38	0	0
2	None	0	0	0
0	Area charge ($1479/ha)	85	70	55
1	Area charge ($1479/ha)	38	0	0
2	Area charge ($1479/ha)	0	0	0
0	Royalty ($\$20/m^3$)	65	50	35
1	Royalty ($\$20/m^3$)	34	0	0
2	Royalty ($\$20/m^3$)	0	0	0
0	Royalty (23%)	62	50	38
1	Royalty (23%)	32	0	0
2	Royalty (23%)	0	0	0

Table I.1. Transition probabilities

		Dipterocarps (D)			Commercial non-dipterocarps (O)			Non-commercial (N)		
j	Diameter class (cm)	a_j	b_{j+1}	m_j	a_j	b_{j+1}	m_j	a_j	b_{j+1}	m_j
1	10-20	0.945	0.022	0.033	0.961	0.012	0.027	0.955	0.012	0.033
2	20-30	0.943	0.036	0.021	0.959	0.022	0.020	0.950	0.017	0.033
3	30-40	0.923	0.052	0.025	0.957	0.025	0.018	0.946	0.015	0.039
4	40-50	0.928	0.047	0.025	0.952	0.021	0.028	0.960	0.031	0.009
5	50-60	0.948	0.035	0.017	0.969	0.024	0.007	0.921	0.018	0.061
6	60-70	0.952	0.044	0.005	0.957	0.034	0.009	0.945	0.023	0.032
7	70+	0.981	0.000	0.019	0.962	0.000	0.038	0.977	0.000	0.023

Source: Boscolo et al. (1997)

Table I.2. Ingrowth equations, by timber group

Dipterocarps (D)			
	Independent variable		
Statistics	Constant	basal area (m^2/ha)	D trees/ha
Coefficient	$3.10 = \alpha_1$	$-0.10 = \beta_1$	$0.017 = \gamma_1$
Standard error	0.99**	0.04*	0.004**
R^2_{adj}	0.32		
Commercial non-dipterocarps (O)			
	Independent variable		
Statistics	Constant	basal area (m^2/ha)	O trees/ha
Coefficient	$3.84 = \alpha_2$	$-0.13 = \beta_2$	$0.017 = \gamma_3$
Standard error	1.02**	0.05*	0.008*
R^2_{adj}	0.09		
Non-commercial (N)			
	Independent variable		
Statistics	Constant	basal area (m^2/ha)	N trees/ha
Coefficient	$13.27 = \alpha_3$	$-0.30 = \beta_3$	$0.017 = \gamma_3$
Standard error	4.14**	0.11*	0.009
R^2_{adj}	0.15		

Source: Boscolo et al. (1997)

Figure 1. Linkages between logging regulations and management outcomes

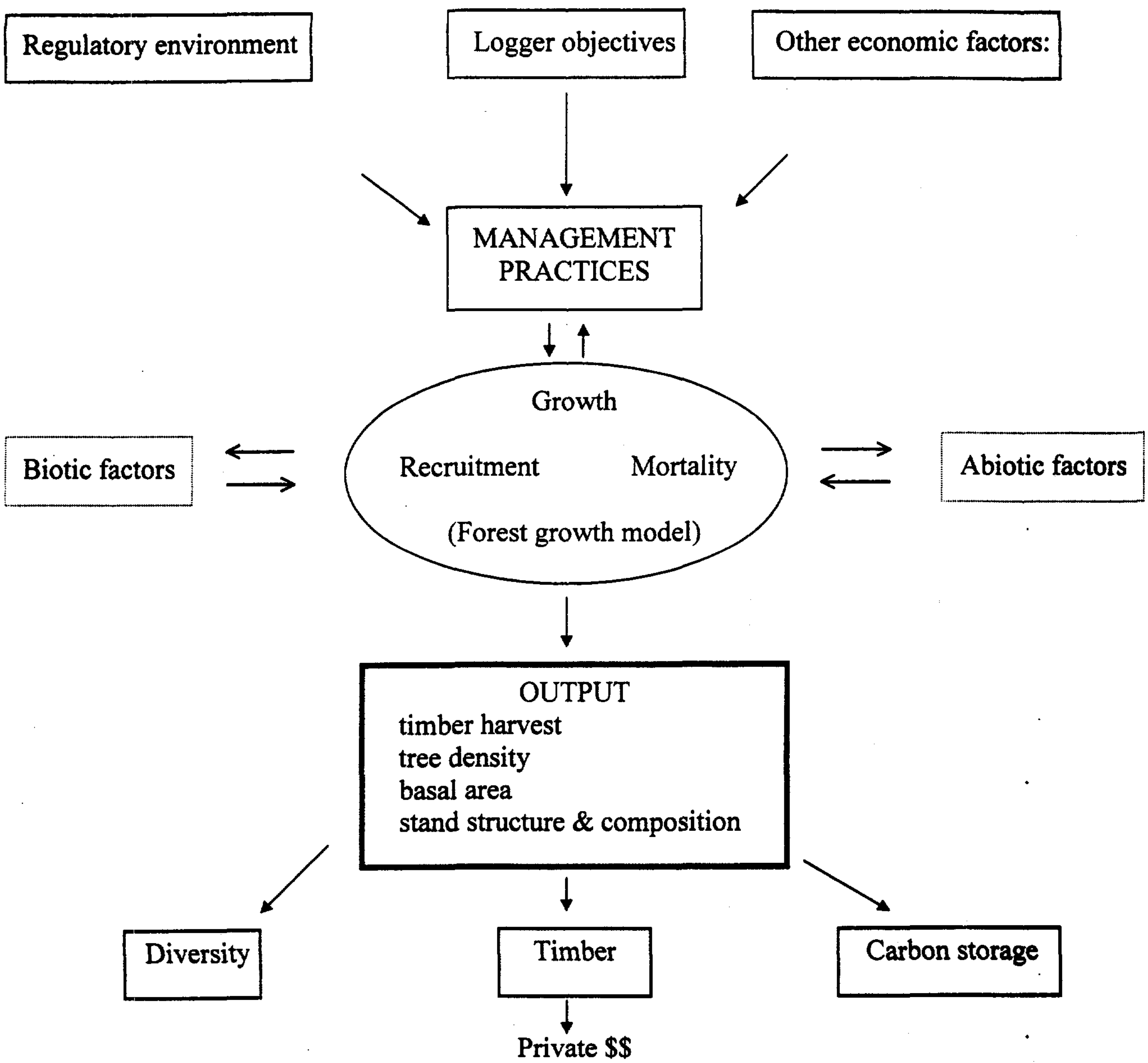


Figure 2. Recovery of carbon storage and basal area after unregulated harvest at year 60

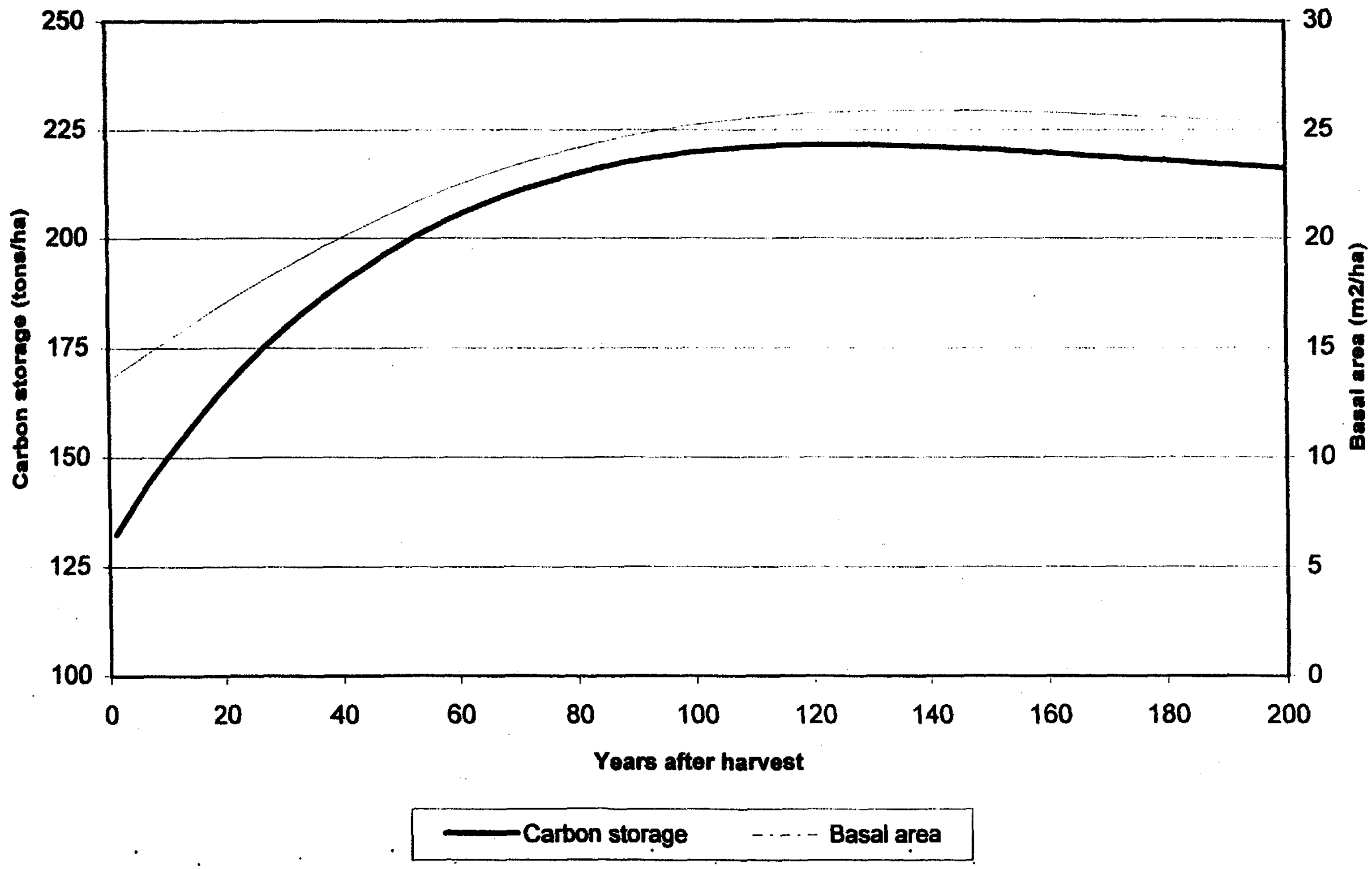


Figure 3. Recovery of diversity index (PCI) after unregulated harvest at year 60

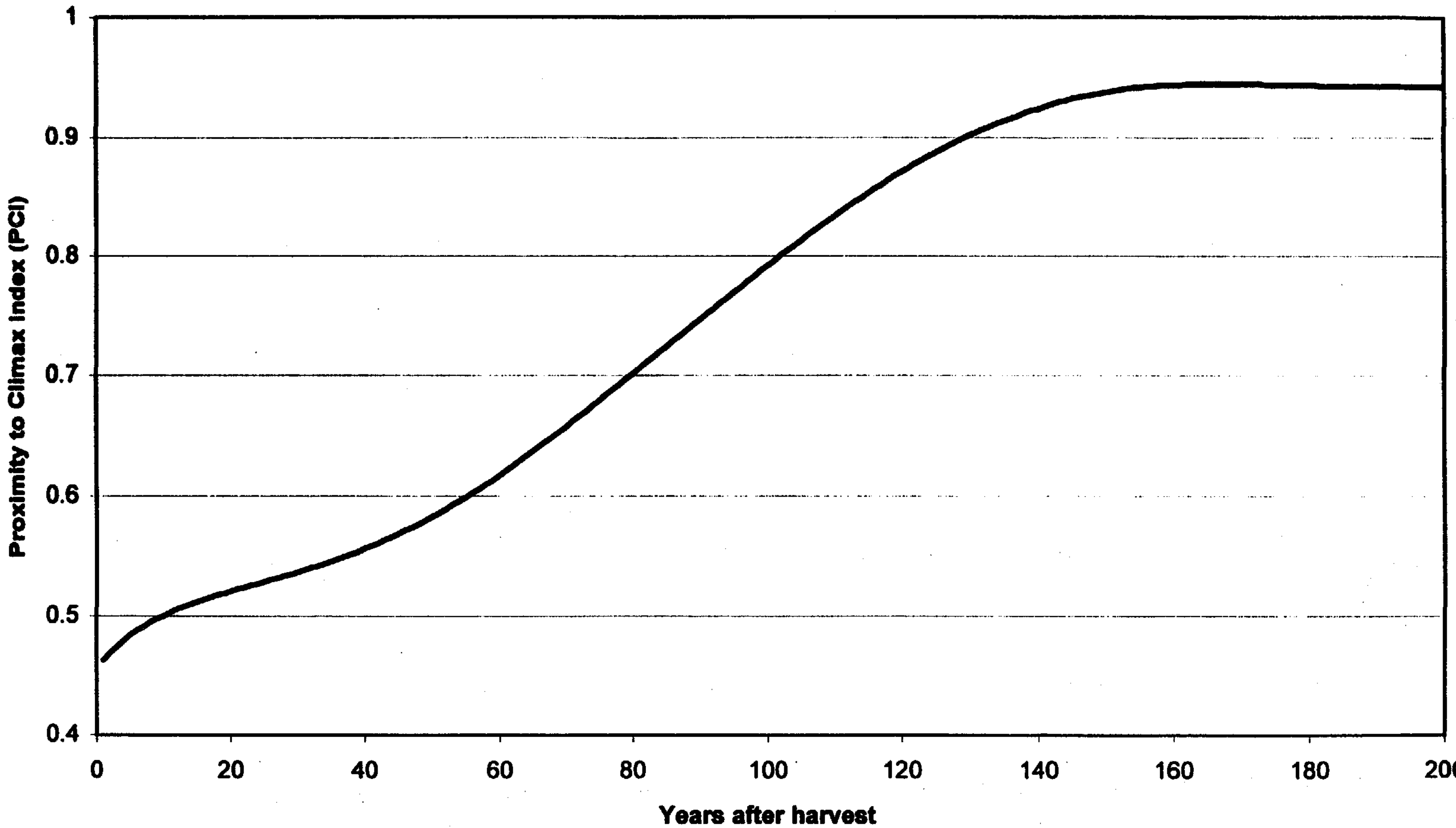


Figure 4. Recovery of basal area after harvesting a virgin stand

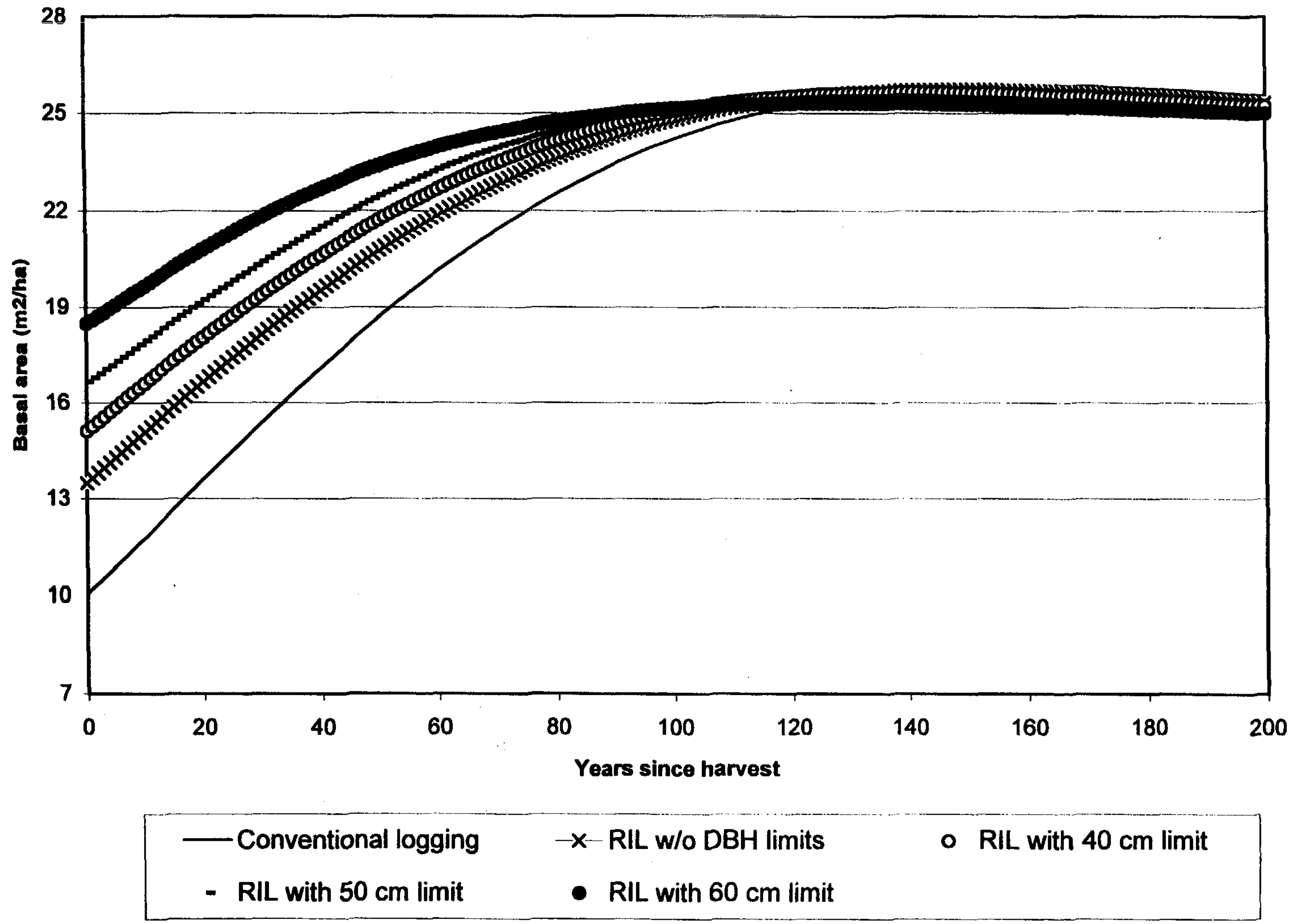


Figure 5. Carbon storage after harvesting a virgin stand

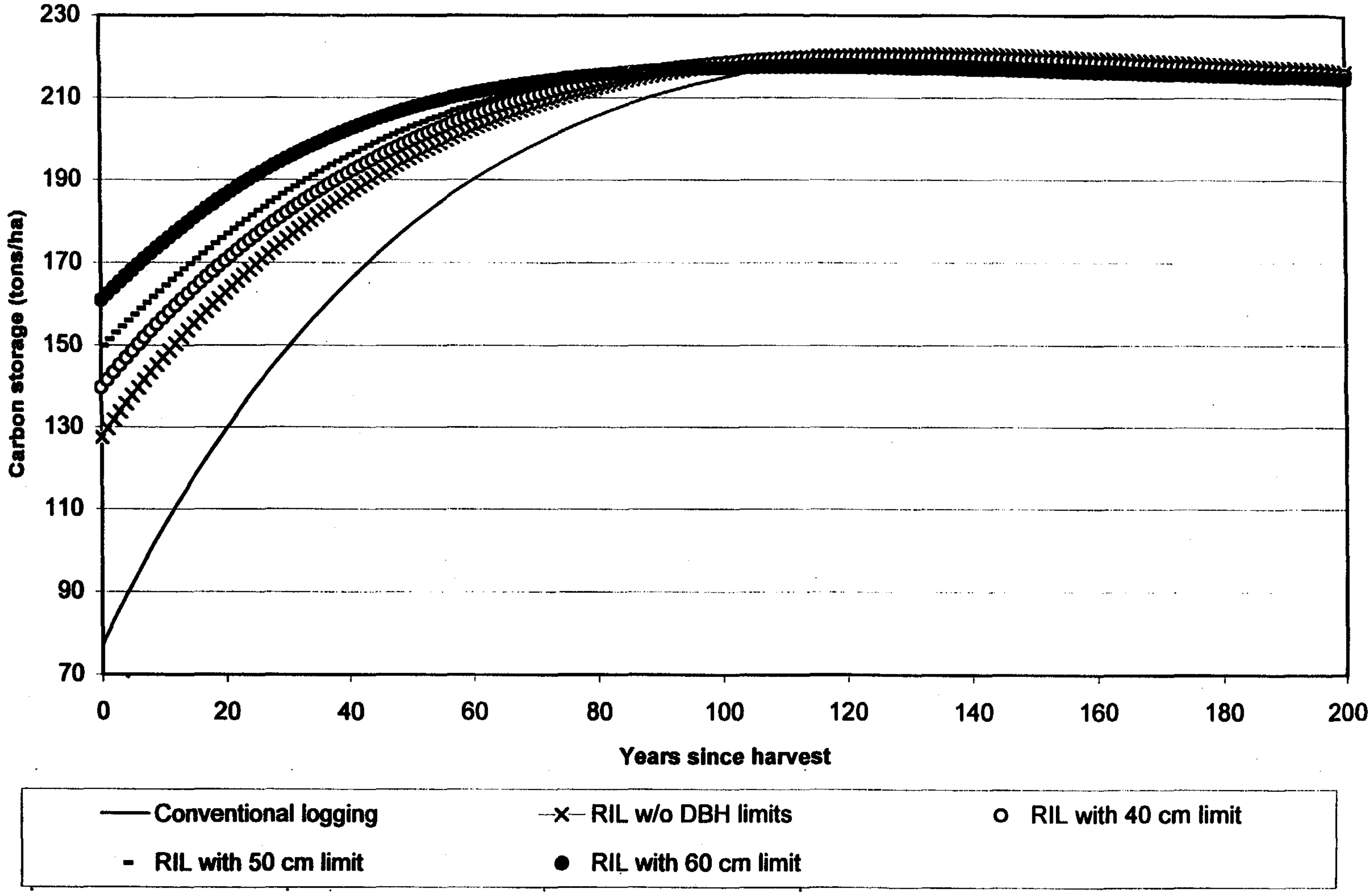
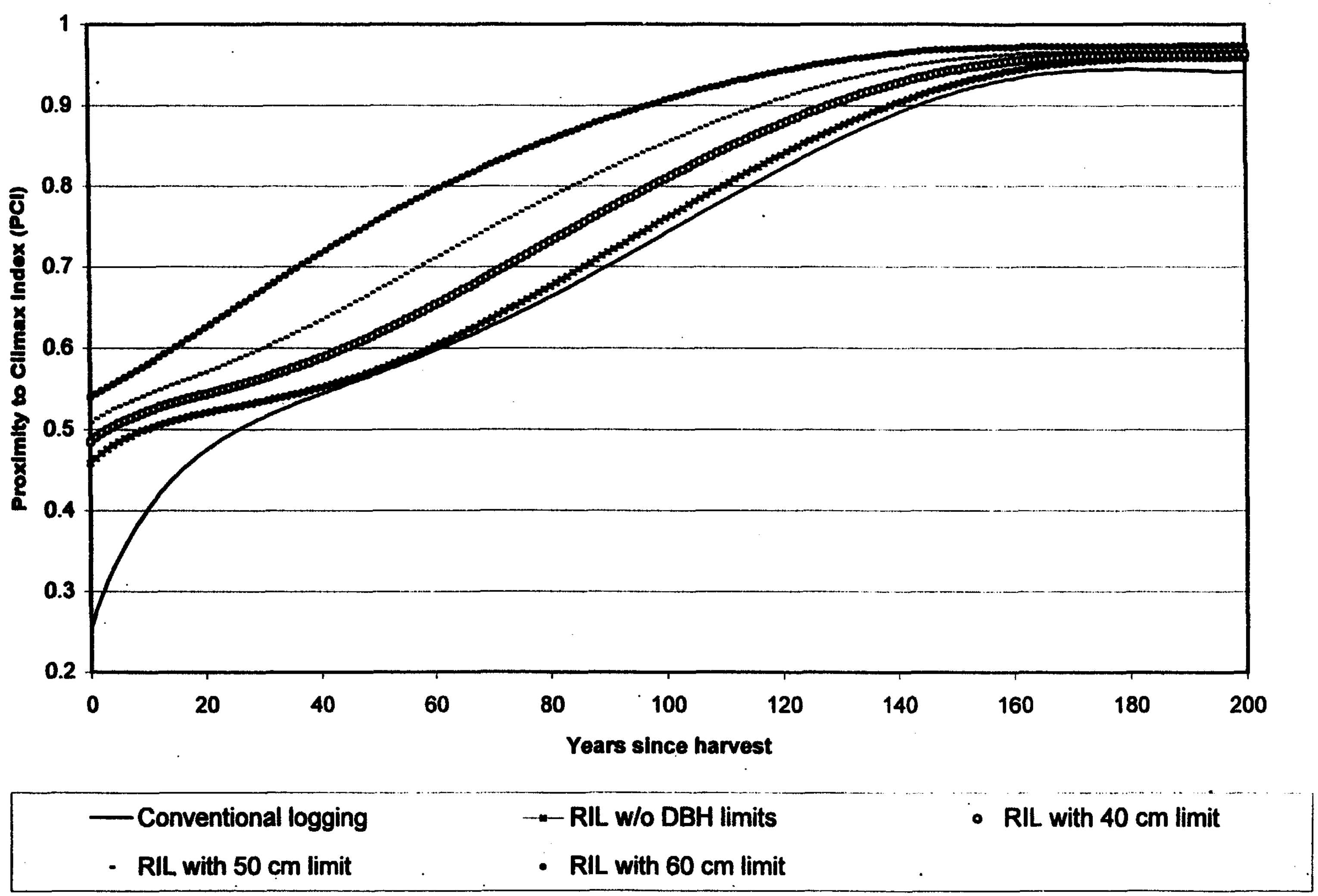


Figure 6. Recovery of Proximity to Climax Index (PCI) after harvesting a virgin stand



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